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MEASUREMENT OF THE CHARGE FORM FACTORS FOR LITHIUM-SIX AND LITHIUM-SEVEN BY ELECTRON SCATTERING

by

William Albert Monson

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THESIS

MEASUREMENT OF THE CHARGE FORM FACTORS FOR LITHIUM-SIX AND LITHIUM-SEVEN BY ELECTRON SCATTERING

by

William Albert Monson

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June 1969

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Measurement of the Charge Form Factors for Lithium-Six and Lithium-Seven by Electron Scattering

by

William Albert Monson
Lieutenant, United States Coast Guard
B.S., United States Coast Guard Academy, 1963

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN PHYSICS

from the

NAVAL POSTGRADUATE SCHOOL
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ABSTRACT

The charge form factors of the stable lithium isotopes, lithium-six and lithium-seven, were measured in the experiment. The root-mean-square radius of Li^6 was determined to be 2.43 F. The root-mean-square radius of Li^7 was determined to be 2.33 F.

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TABLE OF CONTENTS

I. INTRODUCTION ---------- 7

II. EXPERIMENTAL EQUIPMENT AND TECHNIQUE ---------- 10

III. DATA REDUCTION ---------- 13

IV. RESULTS ---------- 20

V. CONCLUSIONS ---------- 22

APPENDIX A ---------- 28

APPENDIX B ---------- 30

BIBLIOGRAPHY ---------- 32

INITIAL DISTRIBUTION LIST ---------- 33

FORM DD 1473 ---------- 35

LIST OF DRAWINGS

Figure

1. Typical Elastic Peak ---------- 23

2. Li^6 Measured Charge Form Factor ---------- 24

3. Ln F vs. q^2 for Li^6---------- 25

4. Li^7 Measured Charge Form Factor ---------- 26

5. Ln F vs q^2 for Li^7 ---------- 27

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I. INTRODUCTION

Some understanding of how nucleons are arranged in the p shell and interact is necessary in forming any good theory of the nuclear structure of heavier and more complex elements. The structure of the lithium nuclei are very important stepping stones because they are the first stable elements in the periodic table containing p-shell nucleons. Electron scattering experiments to date have yielded varying results, the one agreement being an indication that the lithium six isotope is larger than lithium seven [1, 2]. This is a direct violation of the $A^{1/3}$ approximation for the nuclear radius. Investigation of their structure has been severely hampered due to their highly reactive nature, i.e., lithium reacts violently with water and becomes highly contaminated in an extremely short time in air. Target preparation for this experiment is explained in the experimental technique section.

Electron scattering is one of the principal techniques used for nuclear radius investigations. The electron interacts only with the electromagnetic structure of the nucleus and since these interactions are quite small compared to the interactions between nucleons, electron scattering does not disturb the nuclear structure. The results obtained by elastic electron scattering from finite nuclei deviate from the theoretical predictions for scattering from a point nucleus. This deviation, called

the charge form factor, is, when using the Born approximation [3] for a spin-zero nucleus, the Fourier transform of the charge distribution of the nucleus. Determination of the form factor, $F(q^2)$, as a function of the square of the momentum transferred to the nucleus, q^2, leads to a determination of the spatial distribution of the nucleus.

In the experiments performed at this facility, the lithium data were normalized to carbon data taken during the same scattering runs. The reasons for ratio measurements are as follows:

(1) The Mott cross section (the cross section for scattering from a point nucleus) is sensitive to angle and energy. A ratio measurement nearly cancels the errors in the absolute determination of these quantities.

(2) The errors in the experimental cross section due to spectrometer resolution and solid angle cancel in ratio measurements.

(3) Any small error in the calibration of the beam monitor will tend to cancel as long as the beam is kept constant in time.

(4) Radiation and ionization corrections (and errors in them) will tend to cancel provided the targets are prepared with the proper thicknesses.

Most of the elastic electron-scattering experiments performed at other institutions have been normalized to either

carbon or the proton and the majority of the absolute measurements have been made on these two nuclei.

II. EXPERIMENTAL EQUIPMENT AND TECHNIQUE

The design and operation of the Naval Postgraduate School Linear Accelerator has been described in a thesis by Barnett and Cunneen [4] and the subsequent modifications reported in a thesis by Midgarden [5]. Additional improvments to the accelerator complex have been made, especially to the counting system. It had been noticed previously that electrons were penetrating the spectrometer slit material, yielding a small but definite elastic peak even when the slits were completely closed. The scintillator used in the front counter in the spectrometer was re-cut to 0.125 inch, the same size as the separation of the spectrometer slits, to eliminate this problem. The scalars were equipped with new pre-amplifiers and tested to counting rates of 20 megahertz. A correction to the counting results was also derived (see Appendix A) utilizing coincidence counts, accidental coincidences, and the individual counts from the front and back counters.

Environmental background was a major problem on previous experiments conducted with the accelerator and although considerable improvement has been made it still must be considered a major problem. Parafin shielding was installed between the beam dump and the spectrometer, and the concrete shielding around the counters was replaced with parafin. The ceiling in the end station was shielded

with borated parafin as was the concrete wall separating the end station from the beam deflection area. Parafin is an excellent material for slowing neutrons down and the addition of borate to the parafin increases the absorption of neutrons. Concrete and lead shielding is primarily used for absorption of gamma rays. Apparently the stray neutrons present in the end station were contributing more to the background problem than stray gamma rays because the added shielding resulted in a peak-to-background ratio of 200-to-1 on the average.

A protractor was inscribed on the mount for the spectrometer which provided scattering angle determinations within 0.2 degree.

Since lithium reacts with air it was decided that the condition of the targets could be preserved best by leaving the target chamber sealed and under a vacuum once the targets were installed. This required the use of mylar windows in the scattering ports and the spectrometer entrance to permit scattering runs to be made at different angles. Several scattering runs on carbon and aluminum were performed to determine the effect the windows would have. The ratio of the number of electrons elastically scattered by aluminum to the number elastically scattered by carbon remained the same, with or without the windows.

The lithium targets were cleaned and pressed while immersed in mineral oil to a thickness of approximately 50 mils. (Precise measurements were made after the experiments

and yielded for Li^6, t = 42.8 mils and for li^7, t = 57.9 mils.) The scattering chamber was evacuated and then filled with argon. When the chamber top was removed a continuous flow of argon through the chamber was maintained. The lithium targets were removed from the mineral oil, washed in petroleum ether in the argon atmosphere and mounted on the target ladder with a 10 mil carbon target. The chamber was then sealed and evacuated to about 10^{-6} torr.

A graph of the counting correction versus count rate was obtained for the scalars used in the experiment. Although the correction appeared to vary linearly up to count rates greater than 100 counts per second, the rates for these experiments were maintained at less than 10 counts per second. The correction at 10 counts per second was four per cent.

III. DATA REDUCTION

The data from a scattering experiment consist of a spectrum of the number of scattered electrons per integration of the incident beam as a function of the scattered electron energy. A typical elastic scattering peak is shown in Figure 1. The experimental cross section is the necessary result for determination of the form factor. The experimental cross section with no radiative corrections is defined as

$$\left(\frac{d\sigma}{d\Omega}\right)'_{exp} = \frac{N_{sc}}{N_{inc}\, n_t\, \Delta\Omega} .$$

N_{sc} is the number of elastically scattered electrons including the corrections for background, counting rate and accidental coincidences. N_{inc} is the number of electrons incident on the target; n_t is the effective number of target nuclei per cm^2 and $\Delta\Omega$ is the scattering solid angle.

To obtain a cross section from the experimental data the following technique was employed. The total number of scattered electrons per millivolt integration under the elastic peak was obtained from

$$N_{sc} = \sum_i \frac{1}{2} \left(\frac{N_i}{V_i} + \frac{N_{i+1}}{V_{i+1}}\right) \frac{\Delta E_i}{E_i f}$$

where N_i is the number of electrons scattered with energy E_i, ΔE_i is the step size (normally 0.05 MeV), f is the

spectrometer resolution and V_i is the integration voltage of the i^{th} step in millivolts. The number of incident electrons per millivolt integration is calculated from

$$N_{inc} = \frac{C}{e} \cdot K$$

where C is the capacitance of the integrator, K is the reciprocal of the SEM (Secondary Emission Monitor) efficiency and e is the electron charge. The experimental cross section can then be written as

$$\left(\frac{d\sigma}{d\Omega}\right)_{exp} = \frac{N_{sc} e}{C K} \frac{1}{n_t \Delta\Omega}$$

Some electrons will radiate an amount of energy greater than some ΔE and will not be counted in the spectrum. It is necessary to correct for two separate types of radiation events which accompany the scattering process. The first event is the energy loss due to the interaction between the electron and the target nuclei as the electron passes through the material. This correction has been approximated by Bethe and Ashkin [6] and the experimental cross section should be multiplied by

$$K_b = e^{\delta_b},$$

where $\delta_b = \frac{t_o}{\ell n\ 2} \; n \frac{E_i}{\Delta E\ \eta^{3/2}}$, and $t_o = \frac{t}{x_o} \frac{1}{\cos\phi}$. the density of the target, t is the target thickness, x_o is the radiation length of the target material, ϕ is the angle the target makes with the normal to the beam axis, E_i is the incident electron energy, ΔE is the energy

difference from the peak energy to the energy at which the data was terminated, and η is the nuclear recoil factor ($\eta = 1 + \frac{2E_i}{Mc^2} \sin^2 \theta/2$).

The second process is the radiation given off during the large angle scattering event, called "nuclear bremstrahlung." This was first approximated by Schwinger [7] and then amended by Tsai [8] to account for the recoil of the nucleus. The corresponding correction factor may be written as

$$K_s = \delta^s ,$$

where $$\delta_s = \frac{2\alpha}{\pi} \{[\ell n \frac{E_i}{\Delta E \eta^{3/2}} - \frac{13}{12}][\ell n (\frac{2E_i Mc^2}{(mc^2)^2})(1 - \frac{1}{\eta})] + \frac{17}{36}\}$$

Mc^2 is the rest energy of the proton, mc^2 is the rest energy of the electron, α is the fine structure constant and ΔE, E_i and η are as defined previously. These two corrections are multiplicative and the final cross section has the form.

$$(\frac{d\sigma}{d\Omega})_{exp} = (\frac{d\sigma}{d\Omega})'_{exp} K_s K_b$$

The radiative corrections for these experiments increased the experimental cross sections by 8 to 15%.

Mott [9] developed an expression for the relativistic scattering of electrons from point nuclei which, in the center-of-mass reference frame, has the form

$$\left(\frac{d\sigma}{d\Omega}\right)_{Mott} = \left(\frac{Ze^2}{2mc^2}\right)^2 \left(\frac{1-\beta^2}{\beta^4}\right) \frac{1-\beta^2\sin^2\theta/2}{\sin^4\theta/2} ,$$

where $\beta = v/c$. The only modification made to this equation when transforming to the laboratory frame of reference was the inclusion of the nuclear recoil factor, η. Then

$$\left(\frac{d\sigma}{d\Omega}\right)_{Mott} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott,\ CM} \eta^{-1}$$

The equation of the form factor for carbon derived from an harmonic oscillator shell-model potential by Tassie and Barker [10], including the corrections for the charge distribution of the individual protons and the motion of the center of mass, can be written in the form (see Appendix B),

$$F(q^2) = \left[1 - \frac{\alpha a^2 q^2}{2(2+3\alpha)}\right] \exp\left(-\frac{1}{4} q^2 a^2\right) .$$

The most recent work by Bentz [11] yields parameter values of $a = 1.648$ F and $\alpha = 1.056$ for carbon. The form-factor equation can then be written as,

$$F(q^2) = [1 - 0.2775\ q^2] \exp\ (-0.679\ q^2).$$

To obtain the lithium form factors the data were normalized to carbon data obtained during the same run for the reasons mentioned previously. Since, in general,

$$\left(\frac{d\sigma}{d\Omega}\right)_{exp} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} |F(q^2)|^2,$$

the ratio of lithium to carbon yields the following general expression for the lithium form factor,

$$F_{Li}^2 = F_c^2 \left[\frac{(d\sigma/d\Omega)_c}{(d\sigma/d\Omega)_{Li}}\right]_{Mott} \left[\frac{(d\ /d\Omega)_{Li}}{(d\ /d\Omega)_c}\right]_{exp}$$

where F_c^2 is the calculated carbon form factor.

However, if the target nucleus has a magnetic moment, this will also contribute to the scattering of electrons. Both lithium isotopes have magnetic dipole moments (for li^6, $\mu_o = 0.822$ nuclear magnetons and for Li^7, $\mu_o = 3.256$ nuclear magnetons) so the experimental cross sections have magnetic contributions,

$$\left(\frac{d\sigma}{d\Omega}\right)_{exp} = \left(\frac{d\sigma}{d\Omega}\right)_{CH} + \left(\frac{d\sigma}{d\Omega}\right)_{MAG}$$

Suelzle has shown that the magnetic contribution to the Li^6 form factor for $q^2 < 1\ F^{-2}$ is less than 0.1% and so it has been neglected for Li^6 in these experiments.

The magnetic contribution to Li^7 was determined by Pratt, et. al. [12] to be

$$\left(\frac{d\sigma}{d\Omega}\right)_{MAG} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \left(\frac{\hbar^2 q^2}{4M^2c^2}\right)(1 + 2\ \tan^2\theta/2)\left(\frac{J+1}{3J}\right)\mu_o^2\ F_M^2$$

where q, M and μ_o are previously defined, J is the nuclear angular momentum, and F_M is the magnetic form factor. Li^7 also has a 0.478 MeV excited level which yields a transverse contribution to the scattering in the form of M1 and E2

multipoles. Rand et. al. [13] show that this contribution may be combined with the elastic magnetic part to produce a total magnetic form factor which may be written as,

$$F_M^2 = [A\langle j_o\rangle^2 + B\langle j_o\rangle\langle j_2\rangle + C\langle j_2\rangle^2]\, F_N^2$$

where $\langle j_o\rangle = (1 - \frac{2}{3} x)\ \exp\ (- x + \frac{x}{A})$

$$\langle j_2\rangle = \frac{2}{3} x \exp\ (- x + \frac{x}{A})$$

$$x = \frac{1}{4} q^2 a_o^2$$

$$F_N^2 = \frac{1}{(1 + \frac{q^2 a_p^2\ 2}{12})} \quad .$$

Rand's values for the constants were A = 1.27, B = 0.22, C = 1.21, a_o = 1.72F and a_p is the rms radius of the proton, 0.80F. The magnetic correction can then be written as (Suelzle [1]).

$$S_{MAG}^2 = \frac{(d\sigma/d\Omega)_{MAG}}{(d\sigma/d\Omega)_{Mott}}$$

This term is to be subtracted from the experimental form factor.

The longitudinal contribution (C2' multipole) must also be subtracted from the experimental form factor. Willey [14] has calculated this contribution and has shown it to be

$$S^2_{c2'} = \frac{1}{z^2}\frac{1}{4}\left[\langle j_2\rangle D(1 + Gq^2)\right]^2 F_N^2$$

where D = 2, G = -0.0245 for the odd-proton model.

The charge form factor for Li^7 is then

$$F^2_{ch} = F^2_{exp} - S^2_M - S^2_{c2'} .$$

IV. RESULTS

Figure 2 shows the Li^6 form factors as a function of q^2 determined by these experiments. Note that $F \to 1$ as $q^2 \to 0$ as expected, but that the manner in which it does is unusual. Phase-shift analysis of the cross sections might remove the curvature at the low values of q^2 since the Born approximation is not as valid at low energies as phase-shift analysis.

Figure 3 shows the ℓn F versus q^2. The slope of this curve as q^2 approaches zero yields the model-independent rms radius of the charge distribution. If the Li^6 curve is forced through ℓn F = 0 the rms radius is found to be 2.55 F. If the curve is not forced through ℓn F = 0 the rms radius is 2.43 F. Suelzle found the best fit to his data using the phenomenological expression for the form factor

$$F^2(q^2) = \exp(-a^2q^2) - c^2 \exp(-b^2q^2) \ .$$

His rms radius for Li^6 was 2.54F. Bernheim found the simple harmonic-well shell model would fit her data and reported an rms radius of 2.41F. The forced result from these experiments agrees with Suelzle while the non-forced result agrees with Bernheim.

Figure 4 is the plot of the Li^7 form factors as a function of q^2. Again a similar curvature is present at

low q^2. Figure 5 shows the $\ell n F$ versus q^2 and yields a non-forced result of 2.33F for the rms radius of Li^7. If the curve is forced through $\ell n F = 0$ the best fit is obtained for an rms radius of 2.55F. Suelzle fitted a simple harmonic-well model to his data and found an rms radius of 2.39 F. Bernheim also fitted the simple harmonic-well model and found 2.33F for the rms radius of Li^7.

V. CONCLUSIONS

Phase-shift analysis should be applied to the data because of the low energies used in obtaining the low values of q^2. If the curvature is still present in the form factor plot then some serious consideration must be given to the possible existence of a halo around these nuclei and further investigation should be conducted.

Because of the uncertainty mentioned above it is felt that the non-forced curves of the ℓn F as a function of q^2 should be used in the determination of the model independent rms radius of each isotope. These yield an rms radius of 2.43 F for Li^6 and 2.33 F for Li^7. These values are in excellent agreement with the results reported by Bernheim.

Figure 1. Typical Elastic Peak

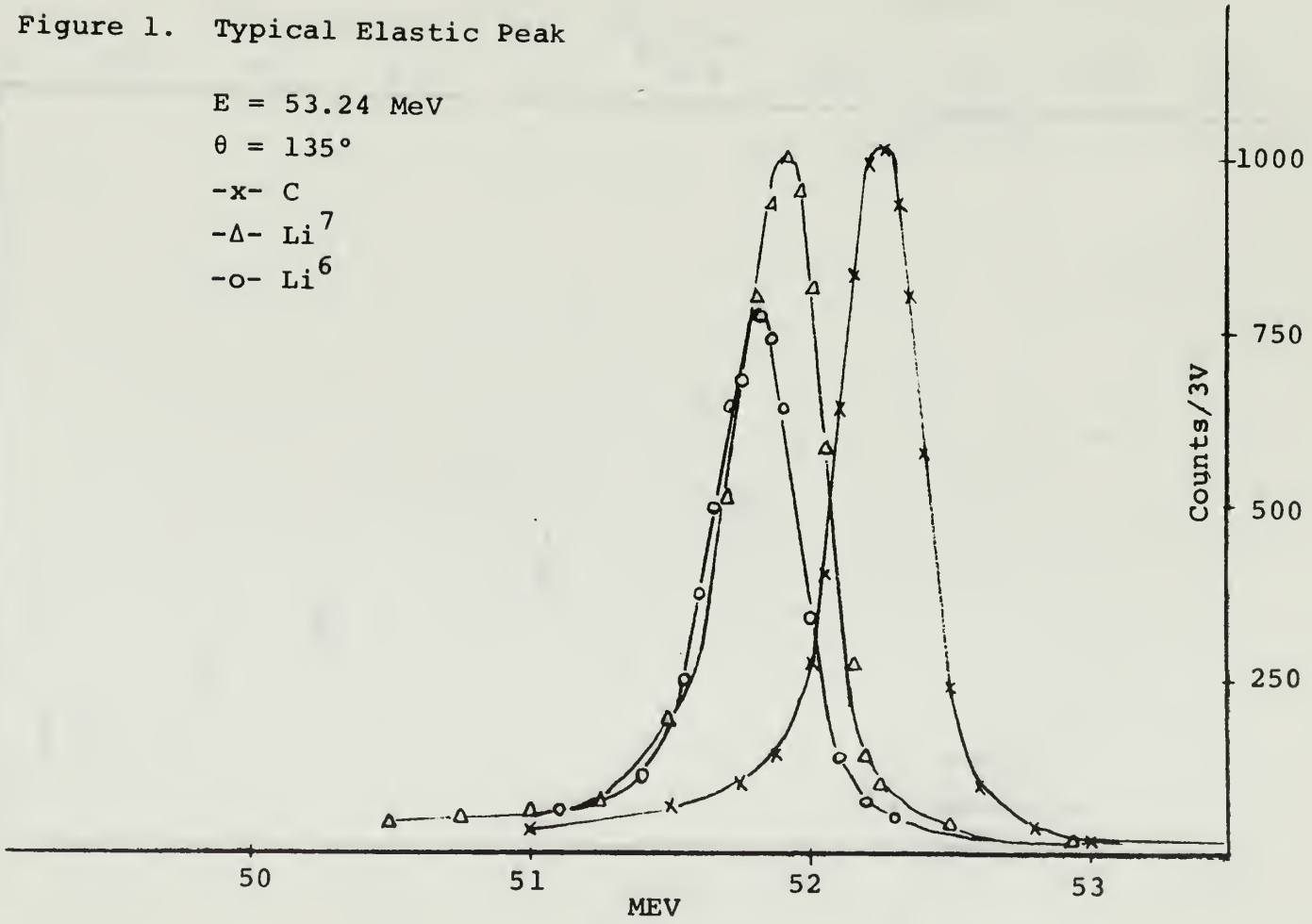


Figure 2. Li^6 Measured Charge Form Factor

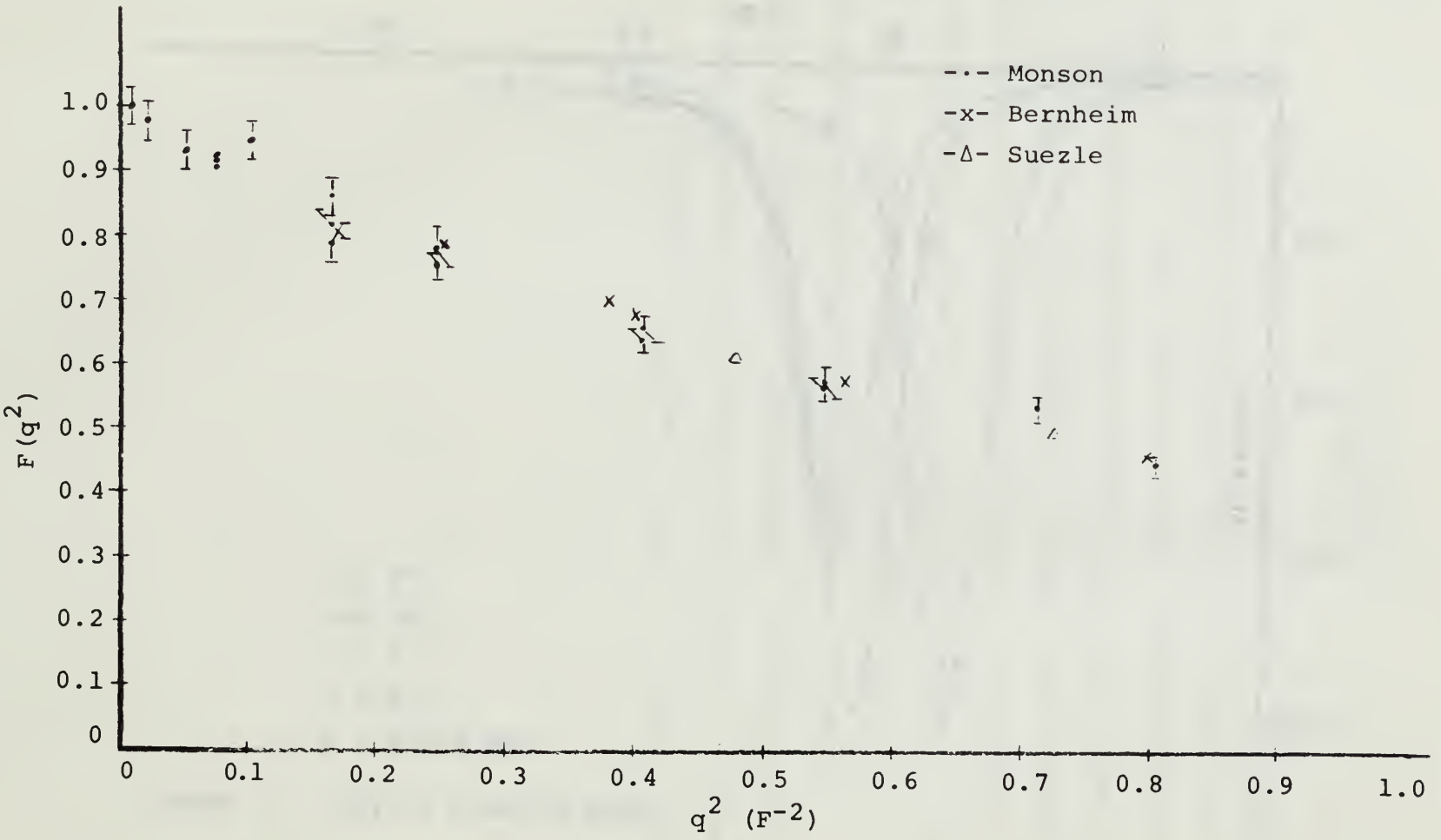


Figure 3

ℓn F vs q^2
for Li^6

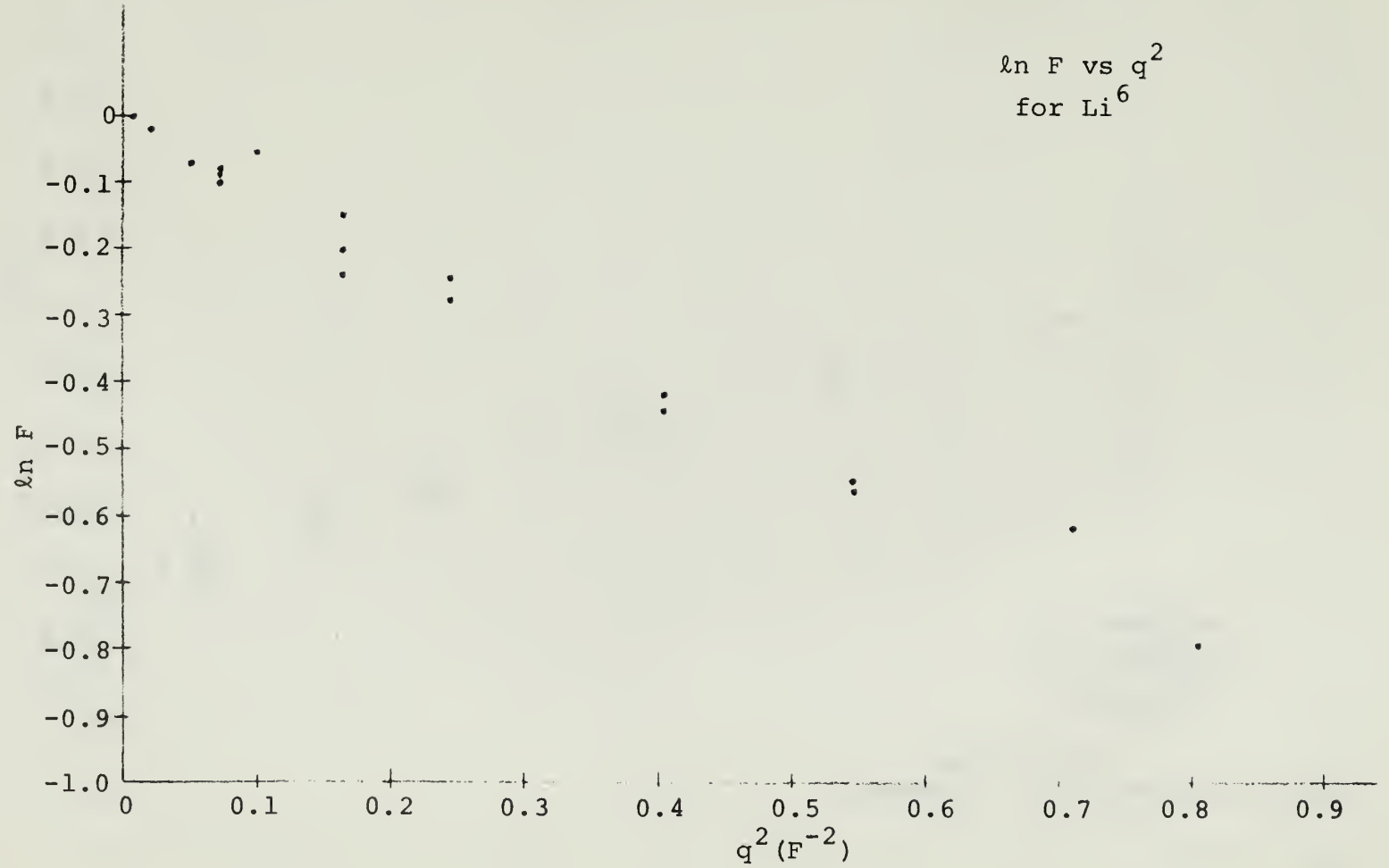


Figure 4. Li^7 Measured Charge Form Factor

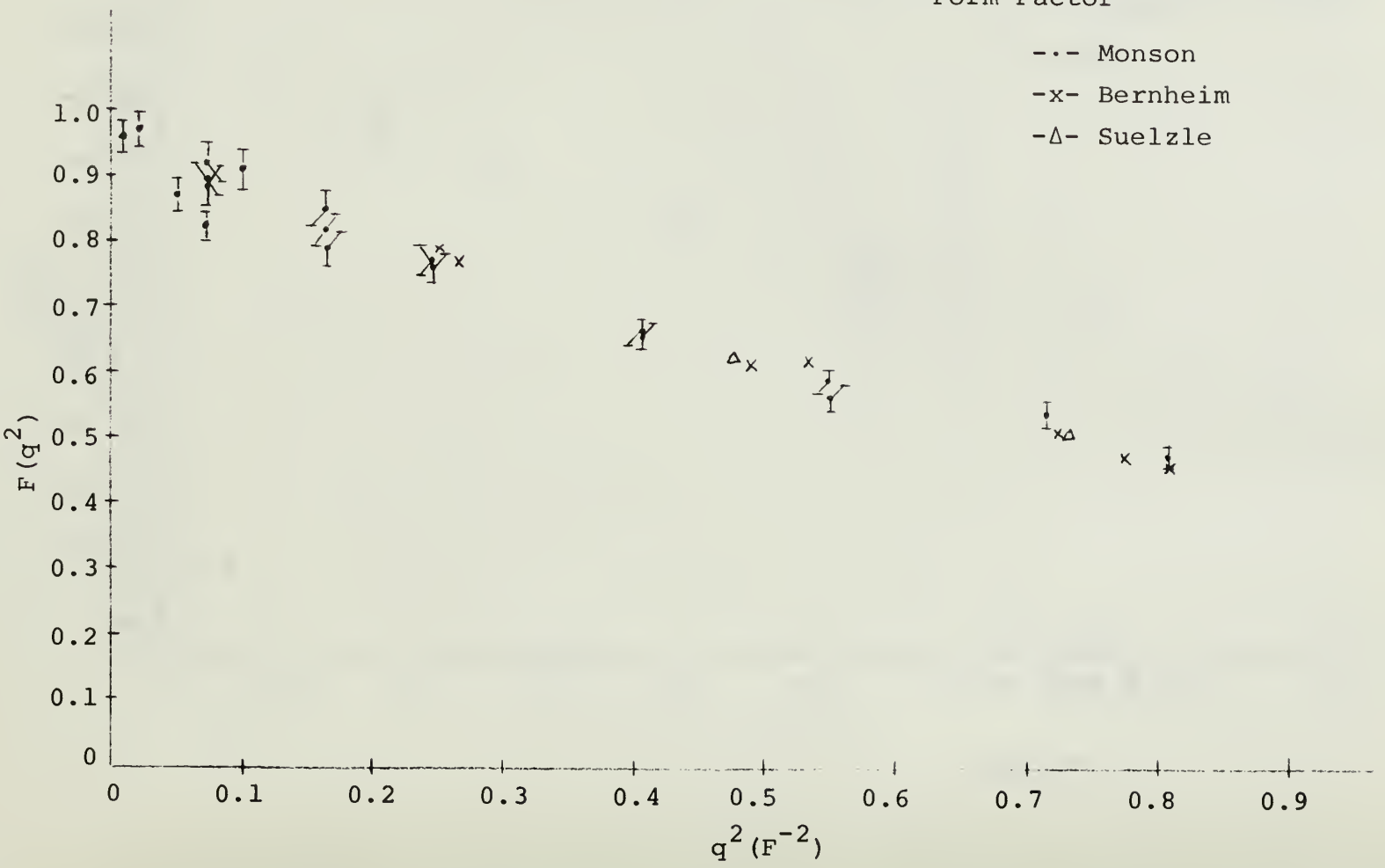
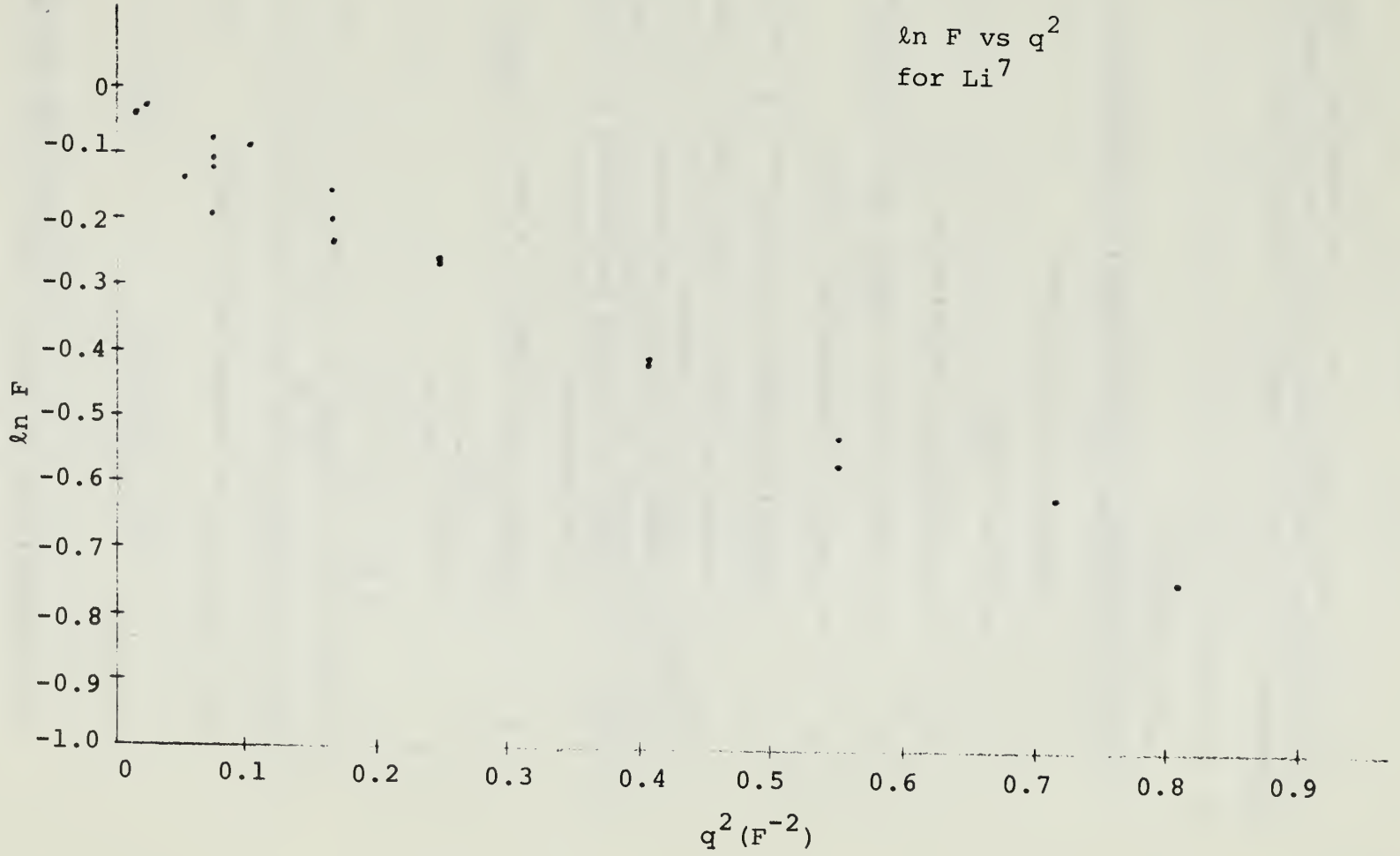


Figure 5

ℓn F vs q^2
for Li^7



APPENDIX A

The following correction to the observed number of scattered electrons is from the unpublished work of Prof. F. R. Buskirk.

Let us define

$P(n,t)$ = probability of counting n electrons in time t

$\mathring{n}$ = average counting rate

t = clock time

τ_c = coincidence registering time

A = number of true counts from a scattering event

B = number of background counts

C_1 = number of counts registered by scalar one

C_2 = number of counts registered by scalar two

C_{12} = number of counts registered in coincidence

C'_{12} = number of counts registered as accidental coincidences

T = actual beam time ($t \times cps \times t_{pulse}$)

$$x = \frac{\tau_c}{cps \times t_{pulse}}$$

$$P = \frac{t}{x} - (C_1 + C_2)$$

$$Q = C_1 C_2 - \frac{t\, C_{12}}{x}$$

Now, for random independent events,

$$P(n,t) = \frac{(\mathring{n}_o t)\ \exp(-\mathring{n}_o t)}{n!}$$

The probability of having one or more counts in a time interval τ_c is

$$P(\eta \geq 1, \tau_c) = 1 - P(o,\tau_c) = 1 - e^{-\mathring{n}_o \tau_c}$$

The probability of a coincidence count registering is

$$P_1 P_2 = (1 - e^{-\mathring{n}_1 \tau_c})(1 - e^{-\mathring{n}_2 \tau_c}) \approx \mathring{n}_1 \mathring{n}_2 \tau_c^{\,2} .$$

Now the total number of accidental coincidence counts in time T is

$$C'_{12} = \frac{T}{\tau_c} (1 - e^{-\mathring{n}_1 \tau_c})(1 - e^{-n_2 \tau_c})$$

$$\approx \frac{\tau_c}{T} C_1 C_2 = \frac{x}{t} C_1 C_2, \qquad (1)$$

since $C_1 = \mathring{n}_1 T$, $C_2 = \mathring{n}_2 T$ on the average.

We also know that the number of counts registered by a scalar is equal to the number of true counts from a scattering event plus the background counts.

$$C_1 = A + B_1 \qquad (2)$$

$$C_2 = A + B_2 \qquad (3)$$

The number of coincidences is equal to the number of true scattering coincidences plus the number of background coincidences.

$$C_{12} = A + \frac{B_1 B_2 x}{t} \qquad (4)$$

Solving the four equations in four unknowns yields

$$A = C_{12 \text{ corrected}} = \frac{-P + \sqrt{P^2 - 4Q}}{2}$$

APPENDIX B

To obtain a concise form for the carbon form factor using the parameters reported by Bentz, et.al., it is necessary to start with the expression for the charge density proposed by Tassie and Barker

$$\rho = \frac{2e}{\pi^{3/2} a^3} \left(1 + \frac{3}{2}\alpha_o \left(1 - \frac{a_o^2}{a^2}\right) + \frac{\alpha o\, a_o^2 r^2}{a^4}\right) \exp\left(-\frac{r^2}{a^2}\right)$$

where $a^2 = \left(\frac{A-1}{A}\right) a_o^2 + \frac{2}{3} a_p^2$, $\alpha_o = \frac{1}{3}(z-2)$

a_p = rms radius of proton.

Now the form factor is the Fourier Transform of the charge density.

$$F(q^2) = \frac{1}{ze} \int \rho(r)\, e^{i\vec{q}\cdot\vec{r}}\, d\vec{r} \quad .$$

Solution of this integral yields

$$F(q^2) = \frac{2}{z}\, e^{-\frac{q^2a^2}{4}} \left[1 + \frac{3}{2}\alpha_o - \frac{3}{2}\alpha_o \frac{a_o^2 q^2}{6}\right],$$

which reduces to

$$F(q^2) = e^{-\frac{q^2a^2}{4}} \left[1 - \frac{\alpha_o a_o^2 q^2}{2(3\alpha+2)}\right] .$$

If we let

$$\alpha = \frac{\alpha_o a_o^2}{a^2 + \frac{3}{2}\alpha_o(a^2 - a_o^2)} ,$$

then

$$F(q^2) = e^{-\frac{q^2 a^2}{4}} \left[1 - \frac{\alpha a^2 q^2}{2(2+3\alpha)}\right] .$$

This is a much simpler form to handle than the expression which Ehrenberg [15] uses. The parameters a and α are also consistent with the ones used by Bentz.

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13. ABSTRACT

The charge form factors of the stable lithium isotopes, lithium-six and lithium-seven, were measured in the experiment. The root-mean-square radius of Li^6 was determined to be 2.43 F. The root-mean-square of Li^7 was determined to be 2.33 F.

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
ELECTRON SCATTERING						
CHARGE FORM FACTOR						
LITHIUM						

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